AD-A045 236 NAVAL UNDERWATER SYSTEMS CENTER NEWPORT R I F/G 20/14

COLLECTED PAPERS ON LOW FREQUENCY ELECTROMAGNETIC DIPOLE SCATTE--ETC(U)

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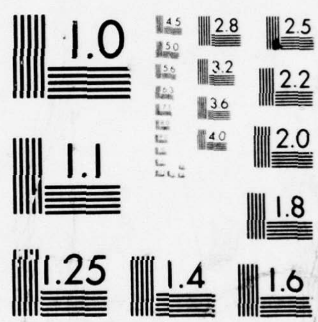

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NUSC Technical Document 5438

Collected Papers On Low Frequency Electromagnetic Dipole Scattering From Conducting Objects In The Ocean

Donald M. Bolle
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30 September 1977

NAVAL UNDERWATER SYSTEMS CENTER
Newport Laboratory

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PREFACE

The information herein was initially presented by the authors at the IEEE Oceans Conferences in 1972, '73, '74, and '76. It was compiled under NUSC Job Order No. C35500.

REVIEWED AND APPROVED: 30 September 1977

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(14) NUSC-TD-5438

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER
TD 5438

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

(9) Technical document,

4. TITLE (and Subtitle)
(6) COLLECTED PAPERS ON LOW FREQUENCY ELECTROMAGNETIC DIPOLE SCATTERING FROM CONDUCTING OBJECTS IN THE OCEAN,

5. TYPE OF REPORT & PERIOD COVERED

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)
(10) Donald M. Bolle
Ronald A. Bowden

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Naval Underwater Systems Center
Newport Laboratory
Newport, Rhode Island 02840

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
Job Order No. C35500

11. CONTROLLING OFFICE NAME AND ADDRESS

12. REPORT DATE
(11) 30 Sep[redacted]977

13. NUMBER OF PAGES
~~20~~ (12) 22p.

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)

15. SECURITY CLASS. (of this report)
UNCLASSIFIED

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)
Electromagnetic dipole scattering
Electromagnetic signatures of submerged bodies
Target detection and classification

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This document, a collection of papers reprinted from OCEANS '72, '73, '74, and '76, traces the development of work conducted by the authors on electromagnetic signatures of smooth conducting objects immersed in the ocean. The papers summarize the successful efforts in applying physical optics approximation techniques to a broad class of problems.

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FOREWORD

This collection consists of papers initially presented by the authors at IEEE Oceans Conferences held in 1972, '73, '74, and '76. It traces the development of their work on the Low frequency electromagnetic signatures of perfectly conducting objects of arbitrary but smooth shape immersed in a lossy medium; i.e., the ocean. The papers summarize their successful effort in applying physical optics approximation techniques to a broad class of problems and in validating this approach, as well as the limits of its applicability, by comparison with the exact solution for a spherical scatterer. This work forms the background for current efforts to extend this approach to scatterers with edges, where the radii of curvature are small compared to the skin depth in the medium.

ELECTRIC AND MAGNETIC DIPOLE SCATTERING FROM A PERFECTLY CONDUCTING SPHERE IN A HOMOGENEOUS LOSSY MEDIUM

D.M. Bolle
R.A. Bowden

Abstract

A comparison of the use of magnetic or electric dipole sources in geophysical exploration and the detection of conducting objects in a lossy environment such as the ocean was made through numerical evaluation of signal levels for orthogonally positioned electric and magnetic transmitter-receiver systems traveling along linear paths near such objects.

Introduction: The problem of detection of spherical bodies in a lossy environment has received considerable attention. An early analysis was presented by March[1] in 1953. Wait[2] presented a complete analysis of the magnetic dipole in the proximity of a sphere of conductivity and permeability different from the conducting medium in which it is immersed. Extensive review articles were published by Ward in 1967 where the geophysical application was stressed[3,4]. However a dearth of published numerical data exists except for some presented in ref. 6 on plane wave scattering from a sphere in a layered earth and, in addition, the orthogonal magnetic dipole transmitter/receiver response on the earth's surface over a buried spherical conducting sphere.

The work reported on here was performed to evaluate the relative merits of electric and magnetic dipole transmitter/receiver systems for the detection of spherical conducting bodies in a lossy medium. The numerical results were obtained for an homogeneous ocean environment. All calculations were based on the analysis as presented by D.S. Jones[5] which follows the earlier work of C.T. Tai which has been republished recently.[7]

For the sake of completeness the basic results are stated for the magnetic and electric dipole sources.

Analytical Results: The electric and magnetic fields for the dipoles can be expressed in terms of the electric and magnetic Herzian vector potentials, i.e.,

$$\underline{E} = \nabla\nabla\cdot\underline{\Pi}_e + k^2\underline{\Pi}_e$$

$$\underline{H} = i\omega\epsilon\,\nabla\times\underline{\Pi}_e$$

and for the magnetic dipole:

$$\underline{E} = -i\omega\mu\,\nabla\times\underline{\Pi}_m$$

$$\underline{H} = \nabla\nabla\cdot\underline{\Pi}_m + k^2\underline{\Pi}_m$$

where

$$\underline{\Pi}_e = \frac{A\underline{p}_o}{4\pi\epsilon}\cdot\frac{e^{i(\omega t-kr)}}{r}$$

$$\underline{\Pi}_m = \frac{B\underline{m}_o}{4\pi}\cdot\frac{e^{i(\omega t-kr)}}{r}$$

and where r is the radial coordinate of a system centered on the dipole source and $A\vec{p}_o$ and $B\vec{m}_o$ are the electric and magnetic dipole moments, respectively. The lossy nature of the medium is included in the dielectric constant; thus

$$\epsilon = \epsilon'(1-i\,\sigma/\omega\epsilon')$$

where σ and ϵ' are the conductivity and dielectric constant of the medium. The propagation constant k is given by

$$k^2 = \omega^2\mu\epsilon \doteq -i\omega\mu\sigma$$

or

$$k \doteq (1-i)/\delta$$

where $\delta = \sqrt{\frac{2}{\omega\mu\sigma}}$ is the skin-depth at the frequency ω and μ is the permeability of the medium; also, we have used the fact that $\frac{\sigma}{\omega\epsilon'} \gg 1$ for the lossy medium at the frequencies of interest.

The fields can be expressed directly in terms of source functions through the use of tensor Green's functions[5]. Thus, for the electric dipole (see figure 1),

$$\underline{E} = -k^2 \frac{A}{\epsilon} \underline{p}_0 \cdot \underline{\underline{\Gamma}}_1(\underline{R}', \underline{R})$$

$$\underline{H} = -i\omega A\, \underline{p}_0 \cdot \nabla \times \underline{\underline{\Gamma}}_1(\underline{R}', \underline{R})$$

and for the magnetic dipole,

$$\underline{E} = -i\omega\mu B\, \underline{m}_0 \cdot \nabla \times \underline{\underline{\Gamma}}_2(\underline{R}', \underline{R})$$

$$\underline{H} = k^2 B\, \underline{m}_0 \cdot \underline{\underline{\Gamma}}_2(\underline{R}', \underline{R})$$

where

$$\underline{\underline{\Gamma}}_1 = \frac{i}{4\pi k} \sum_{n=1}^{\infty} \sum_{m=-n}^{n} d_{mn} \left\{ \underline{q}'^{(r)}_{mn} \underline{q}^{(s)}_{mn} + k^2 \underline{p}'^{(r)}_{mn} \underline{p}^{(s)}_{mn} \right\}$$

where, in turn

for $R' > R$: $r = 4$ and $s = 1$;
and for $R' < R$: $r = 1$ and $s = 4$,

and

$$d_{mn} = (2n+1)(n-|m|)!/[n(n+1)(n+|m|)!]$$

$$\underline{p}^{(s)}_{mn} = \left\{ \frac{im}{\sin\theta} P_n^{|m|}(\cos\theta)\, \underline{a}_\theta - \frac{dP_n^{|m|}(\cos\theta)}{d\theta} \underline{a}_\phi \right\} \cdot Z_n^{(s)}(kR)\, e^{im\phi}$$

$$\underline{q}^{(s)}_{mn} = \left\{ \frac{n(n+1)}{R} Z_n^{(s)}(kR) P_n^{|m|}(\cos\theta)\, \underline{a}_R + \frac{1}{R} \frac{d}{dR}\left(R Z_n^{(s)}\right) \cdot \left[\frac{dP_n^{|m|}}{d\theta} \underline{a}_\theta + \frac{im}{\sin\theta} P_n^{|m|}(\cos\theta)\, \underline{a}_\phi \right] \right\} e^{im\phi}$$

and

$$Z_n^{(1)}(kR) = j_n(kR) \;,\; Z_n^{4}(kR) = h_n^{(2)}(kR)$$

the prime on $\vec{p}$ and $\vec{p}$ indicates that r, θ and ϕ are replaced by r', θ', and ϕ'. It is readily shown that $\underline{\Gamma}_2$ takes the same form as $\underline{\Gamma}_1$.

For either type of dipole, the Green's tensor consists of the sum of two parts; one part for the incident field, and one for the scattered field. Thus,

$$\underline{\Gamma}_1 = \underline{\Gamma}_{i1} + \underline{\Gamma}_{s1}$$

and

$$\underline{\Gamma}_2 = \Gamma_{i2} + \underline{\Gamma}_{s2}$$

where

$$\underline{\underline{\Gamma}}_{s1}(\underline{R}, \underline{R}') = \frac{i}{4\pi k} \sum_{n=1}^{\infty} \sum_{m=-n}^{n} \cdot \left\{ \alpha_{mn}\, \underline{q}^{(4)}_{mn} \underline{q}'^{(4)}_{mn} + k^2 \beta_{mn}\, \underline{p}^{(4)}_{mn} \underline{p}'^{(4)}_{mn} \right\}$$

and α_{mn} and β_{mn} are unknown coefficients. $\underline{\Gamma}_{s2}$ has the same form but different coefficients a_{mn} and b_{mn}.

The boundary conditions, that the tangential electric field must vanish on the sphere, are given by

$$\vec{a}_R \times \vec{E} = 0$$

or

$$\begin{cases} \vec{a}_R \times \underline{\Gamma}_e = 0 \\ \vec{a}_R \times (\nabla \times \underline{\Gamma}_m) = 0 \end{cases}$$

on $R = a$. This leads to the result

$$\alpha_{mn} = -d_{mn} \frac{\frac{d}{dZ}\left(Z j_n(Z)\right)}{\frac{d}{dZ}\left(Z h_n^{(4)}(Z)\right)}$$

$$\beta_{mn} = -d_{mn}\, j_n(Z)/h_n^{(4)}(Z)$$

$$a_{mn} = \beta_{mn}$$

$$b_{mn} = \alpha_{mn}$$

where $Z = ka$.

Using the relation

$$P_n(\cos\gamma) = \sum_{m=-n}^{n} \frac{(n-|m|)!}{(n+|m|)!} P_n^{|m|}(\cos\theta') P_n^{|m|}(\cos\theta)\, e^{im(\phi-\phi')}$$

the series for $\underline{\Gamma}_1$ can be summed over m to obtain

$$\underline{\underline{\Gamma}}_1(\underline{R}, \underline{R}') = \frac{i}{4\pi k}\left[k^2 \underline{a}_R + \nabla \frac{\partial}{\partial R}\right]\left[k^2 \underline{a}_{R'} + \nabla' \frac{\partial}{\partial R'}\right] R R' V_1(R, R') + \frac{ik}{4\pi} (\underline{R} \times \nabla)(\underline{R}' \times \nabla) V_2(\underline{R}, \underline{R}')$$

where, for $R < R'$

$$V_1(R, R') = \sum_{n=1}^{\infty} \frac{2n+1}{n(n+1)} \left[j_n(kR) + \Gamma_n h_n^{(2)}(kR) \right] \cdot h_n^{(2)}(kR') P_n(\cos\gamma)$$

$$V_2(R, R') = \sum_{n=1}^{\infty} \frac{2n+1}{n(n+1)} \left[j_n(kR) + \delta_n h_n^{(4)}(kR) \right] h_n^{(2)}(kR') P_n(\cos\gamma)$$

and

$$\gamma_n = \alpha_{mn}/d_{mn}$$

$$\delta_n = \beta_{mn}/d_{mn} \quad .$$

When $R > R'$, R and R' are interchanged in the expressions for V_1 and V_2. The only changes for the magnetic dipole case are in V_1 and V_2 where

$$G_n = a_{mn}/d_{mn}$$

$$D_n = b_{mn}/d_{mn}$$

replace γ_n and δ_n.

This completes the formal statement of the solution to the problem of an electric or magnetic dipole in the presence of a conducting sphere immersed in a homogeneous lossy medium.

Results: All computations were performed for a medium of conductivity of 4 mhos/meter, i.e., approximating that of sea water. The geometric dimensions are all normalized with respect to skin depth which is used as the characterizing dimension, while the field strengths are normalized with respect to the dipole strengths which, for the electric dipole, becomes

$$\frac{4\pi}{p}\,\delta^3\underline{E} \text{ and } \frac{4\pi}{p}\,\delta^2\underline{H}$$

while for the magnetic dipole case we have

$$\frac{4\pi}{m}\,\delta^3\underline{H} \text{ and } \frac{4\pi}{m}\,\delta^4\underline{E}$$

with the resulting normalized field strengths expressed in db's.

Some sample results for the system shown in figure 2 are given in figures 3(a)-(g) for the electric dipole source with an orthogonally mounted magnetic dipole sensor for various combinations of source-sensor separation b and sphere radii a. The observed signal level in the sensor is shown along linear paths at various stand-off distances s from the sphere.

Figures 4(a)-(g) cover the same situations but with a dipole source substituted for the electric dipole. In appropriate cases, i.e. when the sphere radius is large compared to the baseline or source-sensor separation, the comparison with the infinite plane result is shown for reference purposes.

For the first case the results conform to expectations. As the sphere is approached the signal strength increases monotonically, maximizes at the nearest point, then monotonically decreases as the sphere recedes. Only when the baselengths becomes of the order of the skin depth and the stand-off distance s is small do departures occur from this simple behavior and the curves show marked asymmetry. This effect is to be ascribed to the fact that there occurs strong interaction first between receiver and sphere upon approach followed by strong interaction between transmitter and sphere as one recedes which effects are separated by the long baseline of the system.

In the second case it is seen that the signal level again increases monotonically upon approach but at a position close to the nearest point the spinal level decreases abruptly to a local minimim. This effect is only observed for the case where the source-sensor separation b is much smaller than the sphere radius. As the baselength b becomes comparable to the sphere radius this effect is no longer observed while for long baselengths, i.e., $b \simeq \delta$, one obtains approximately Gaussian response curves again but for the small departures at small stand-offs s due to the effect mentioned earlier. This dip in the response curve for small baselengths to sphere radius ratios is most useful for accurate location of the near approach point to a highly conducting inclusion in a conducting medium and has been observed earlier in some results presented in reference 4. The physical basis for this effect is understood readily upon consulting figure 5 and utilizing the image dipole approximation. At the position of nearest approach (position A) the image generates a relatively small signal in the receiver but as the systems moves away from this point (position B) the image rotates due to the sphere curvature with a resultant increase in the received signal level in the orthogonally oriented sensor. Of course, as the system moves further out, the field and thus the received signal must eventually become weaker.

Conclusion: Numerically computations were made comparing the effectiveness of electric and magnetic dipole sources in source-sensor systems for the detection of highly conducting spherical inclusions in a moderately conducting environment such as the ocean. Differences in response were noted for the magnetic versus electric dipole transmitter systems where the source and sensor are oriented orthogonally so as to yield small signals in a homogeneous environment. The particular feature noted was the nearest point local minimum obtained for the magnetic dipole source system.

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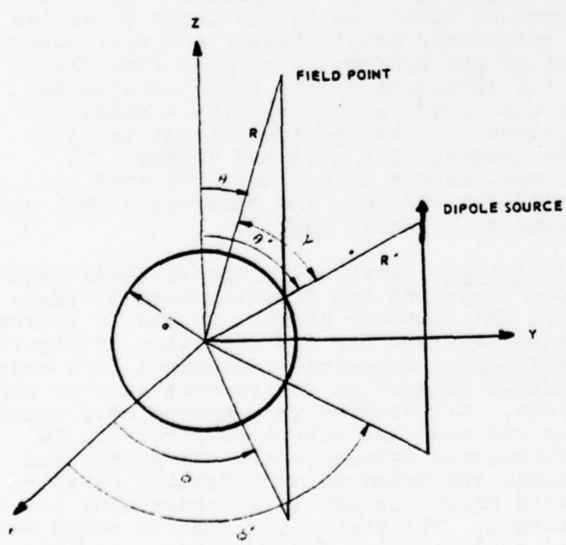

Figure 1. Coordinate System

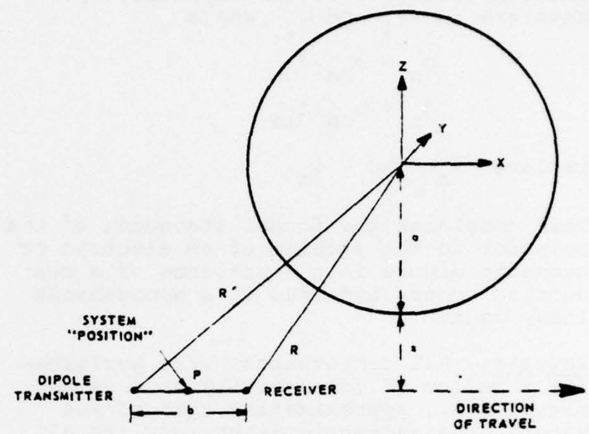

Figure 2. Problem Geometry For Computer Output

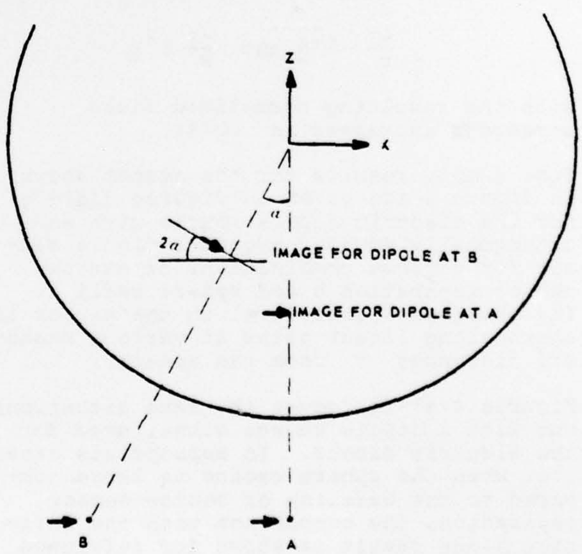

Figure 5. Explanation Of Curve Shape In Figure 4

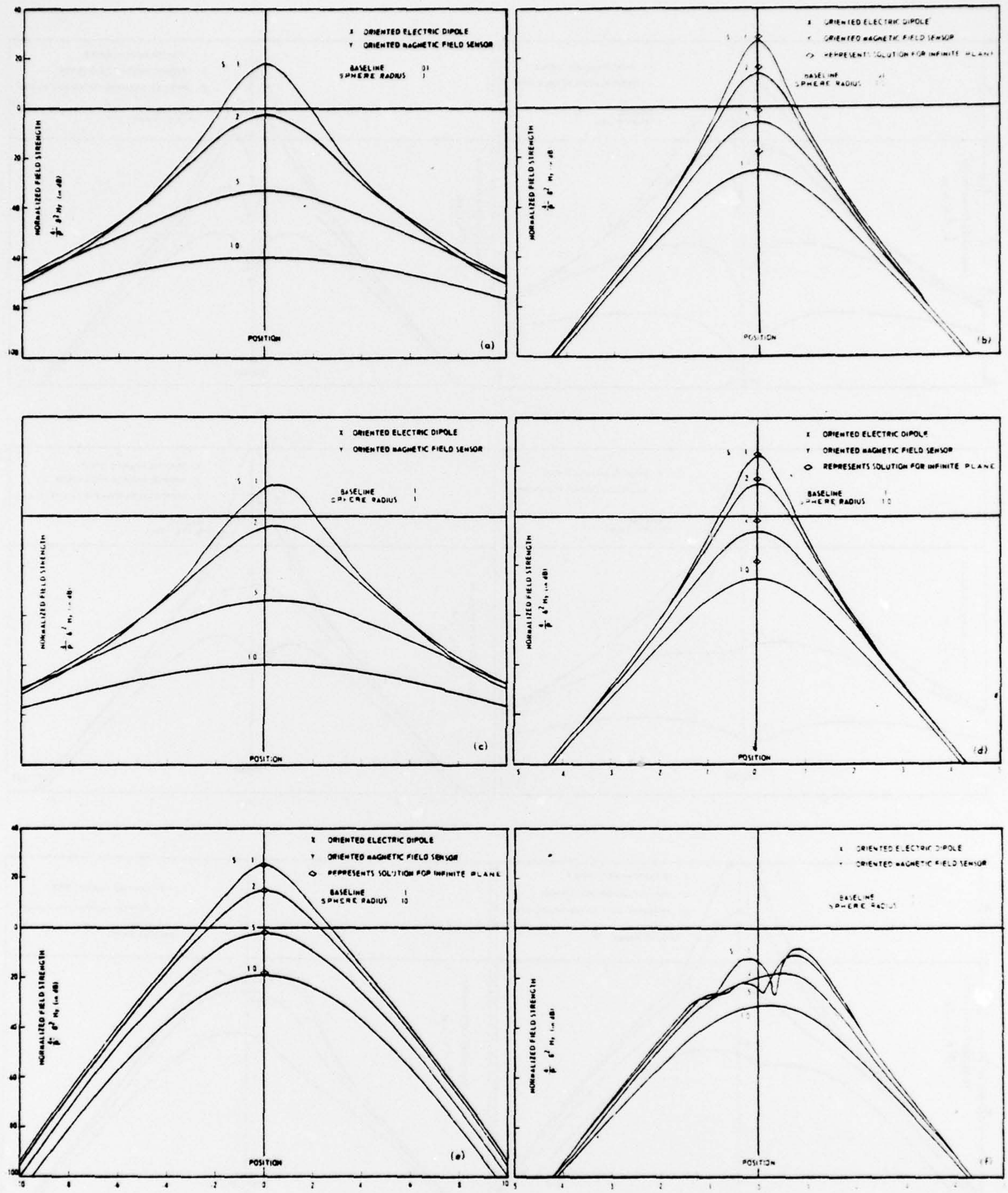

Figure 3. X-Oriented Electric Dipole
Y-Oriented Magnetic Field Sensor

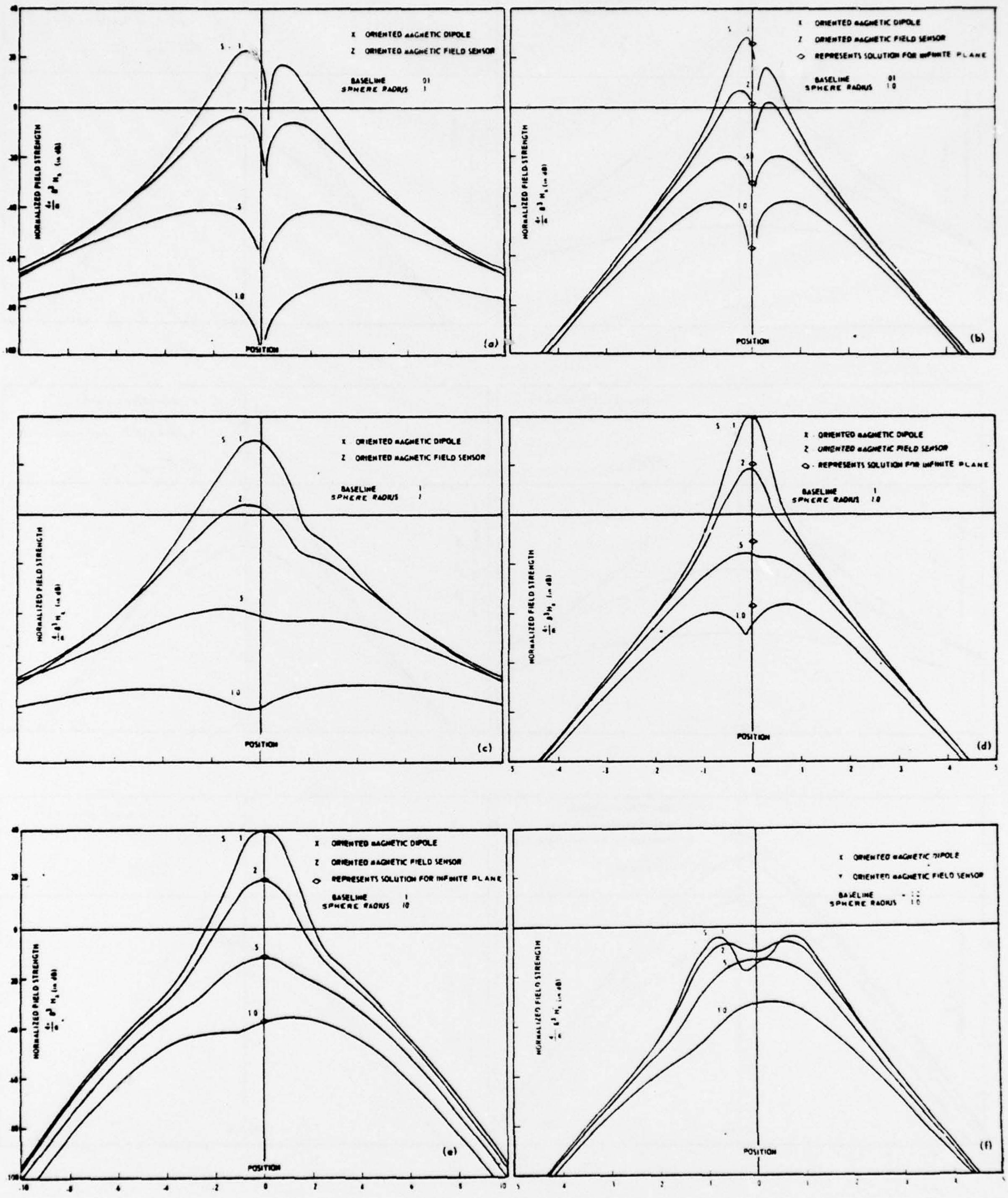

Figure 4. X-Oriented Magnetic Dipole
Z-Oriented Magnetic Field Sensor

THE LOW FREQUENCY ELECTROMAGNETICS SIGNATURES OF CONDUCTING OBJECTS IN THE OCEAN

D.M. Bolle
R.A. Bowden

Reprinted, with permission, from OCEANS '73, IEEE Publication No. 73 CHO 774-0 OCC, pp. 202-205. (Conference held 25-28 September 1973 at the Washington Plaza Hotel, Seattle, Washington.)

ABSTRACT

The utility of the physical optics approximation is explored for the computation of electromagnetic fields of dipole sources in the neighborhood of conducting bodies of diverse shape in a lossy environment such as the ocean. Excellent agreement with previous exact results is obtained for spheres down to one skin depth diameter with source-detector separation up to one skin depth. Only when the sphere size is reduced to one-tenth skin depth do errors in excess of three decibels begin to appear. Such comparisons have confirmed the accuracy of the method for application to non-spherical body shapes. The computer program allows investigation of the response for orthogonally oriented source and detection dipoles in the presence of smooth, curved, conducting bodies in a homogeneous lossy medium. Results are given for spheres, infinite cylinders, prolate spheroids and super-elliptic spheroids exposed to magnetic dipole sources.

INTRODUCTION

The detection and identification of submerged bodies, now considered a classical problem, has seen a great deal of ingenuity applied to theoretical and experimental methods for its solution. Numerous systems have been proposed, many have seen realization (at least in pilot form) and have been subjected to considerable refinement and sophistication. Sonar technology has been heavily dominant in this field but in recent years the electromagnetic spectrum has been closely scrutinized for possible contributions to this complex field. The frequency bands considered range from the optical region (laser technology) to low frequency electomagnetic waves. Effective utilization of the far greater part of the electromagnetic spectrum is blocked by the characteristic nature of the medium. The scattering and loss properties of the ocean severely limit the usable frequency bands. This meant that much effort was directed towards Electrostatic and Magnetostatic modes of operation. Both sources and detectors have been, and continue to be, the subject of intensive investigations.

There are, in addition to the advantages of using static electromagnetic systems, peculiar advantages to using low frequency time varying electromagnetic systems. One obvious attractive feature is the inherent advantage of detection, discrimination and processing of time varying signals in a noisy environment where the frequency is precisely known and controlled. In addition, as will be shown in this paper, it is possible to develop signal signatures for a large class of electrically highly conducting bodies where such bodies are submerged in the ocean. Contrary to the extreme mathematical and computational complexities which arise when the acoustic backscattered signal from a submerged body of complex shaped must be obtained it will be show that a relatively simple methodology suffices when such targets are considered in the low frequency electromagnetic field.

The methodology that is being developed here has the inherent capability of supplementing current standard techniques in the detection and identification of bodies submerged in shallow as well as the deep ocean environment. Geophysical exploration, off-shore technology and many other associated fields can benefit from a detailed knowledge of the electromagnetic signatures of bodies whose conductivities differ substantially from that of the ocean and the ocean bottom. Search and rescue operations and the recovery of lost equipment and material in ocean operations would stand to benefit from the further developments of this aspect of the technology.

An earlier paper (Ref. 1) presented an exact solution for spherical conducting bodies in the ocean. Even for such a simple case the computational effort was considerable and a more general and manageable, though approximate, method is sought for bodies of more complex shape.

Physical optics suggested itself for two reasons. First, in a lossy medium the influence of the source is strong only over a limited part (about one skin depth in radius) of the illuminated region. Further, any creeping waves are sufficiently attenuated so that, for the class of smooth scatterers considered here.

induced surface currents may be reasonably approximated by physical optics. Second, the physical optics approximation is simple and readily implemented for objects of arbitrary shape. The induced surface current is given by

$$\underline{J} = 2\underline{n} \times \underline{H}i$$

where $\underline{n}$ is the outward normal and $\underline{H}_i$ is the incident magnetic field intensity. That is, it is assumed that the surface current induced at a point on a curved surface is that which would be induced on an infinite flat plane tangent to the surface at that point. Thus, physical optics results become exact for any geometry for which image theory will also yield a solution.

Computer subroutines covered geometries for the infinite plane, infinite cylinder, sphere, oblate and prolate spheroids, and a superelliptic spheroid with an elliptic section on the longitudinal axis and a superelliptic section in the transverse plane. Excluded at present are scatterers with sharp edges or ridges.

Since the scattered field intensities are given in terms of an integration over the induced surface current distribution, the surface must be suitably scanned and the integration replaced by a summation. The integration over the surface was performed by projecting points onto the scattering surface from suitably placed points on a plane tangent to the scattering surface at the point nearest the source. Two checks are made: one to ensure that only the illuminated part of the surface is included in the summation, and a second to terminate the process when the contribution from the last scan circle is small compared to the total sum.

The program was first checked for the infinite plane. For one-tenth skin depth increments in scan circle radii and in scan point spacing on the scan circles, agreement with image theory was within one percent.

A comparison is also made between the physical optics approximation and the exact solution for the sphere. Agreement exceeded expectation, and noticeable quantitative error occurs only for sphere radii of one-tenth skin depth or smaller in combination with transmitter-receiver base lengths of one-tenth skin depth or larger and even in these cases the qualitative results were adequate.

THEORY

The field components of a magnetic dipole are given, for a lossy medium, by,

$$E_\phi = \frac{|m|}{4\pi\delta^4} \cdot \frac{2}{i\sigma(r'/\delta)^2} (1 + ikr')\sin\theta' e^{-ikr'}$$

$$H_{r'} = \frac{|m|}{4\pi\delta^3} \cdot \frac{2}{(r'/\delta)^3} (1 + ikr')\cos\theta' e^{-ikr'}$$

$$H_{\theta'} = \frac{|m|}{4\pi\delta^3} \cdot \frac{1}{(r'/\delta)^3} (1 + ikr' - k^2r'^2)\sin\theta' e^{-ikr'}$$

where

$|m|$ = magnetic dipole moment (absolute value),

and the primed variables refer to the spherical coordinate system centered on the dipole location with the z - axis in the direction of the dipole. The propagation factor k is given by

$$k = (1 - i)/\delta$$

where $\delta = (2/\omega\mu\sigma)^{1/2}$ is the skin depth and

ω = angular frequency

μ = permeability of the medium

σ = conductivity of the medium

The field intensities are expressed in this way so that the magnetic fields components $H_{r'}$ and $H_{\theta'}$ may be normalized with respect to the quantity $|m|/4\pi\delta^3$.

Having obtained the induced current $J(x_b,y_b,z_b)$ at some point on the surface of the scattering body, and the area element ds, the scattered field $H_s(x_f,y_f,z_f)$ at a given point is given by

$$\underline{H}_s = \frac{1}{4\pi}\int_s \underline{J} \times \nabla (e^{-ikr_o}/r_o)ds$$

where r_o is the distance separating these two points. Or, in terms of a finite summation

$$H_s(x_f,y_f,z_f) = \frac{1}{4\pi}\sum_{p,q} \underline{J}(x_b,y_b,z_b) \times \nabla(e^{-ikr_o}/r_o)\Delta s_{pq}$$

$$= \frac{1}{4\pi}\sum_{p,q} \frac{e^{-ikr_o}}{r_o^2} (\underline{J} \times \underline{a}_{r_o}) (1 + ikr_o)\Delta s_{pq}$$

where $\underline{a}_{r_o}$ is the unit vector directed from the body point to the field point and p,q are scan parameters.

Some results are illustrated in figures 1 through 6. In every case the calculations were performed for a system using a magnetic dipole as the source and a magnetic field sensor oriented normal to it so that a zero output results in the absence of the scattering body. The abscissa shows the position of the midpoint of the transmitter-receiver baseline as a straight line path is traversed past the perturbing object. The parameter associated with each curve gives the distance of closest approach or standoff. The ordinate gives the

normalized magnetic field intensity. The solution for an infinite plane scatterer, when shown for comparison, is indicated by the diamond shape.

Figures 1 through 4 compare the physical optics approximation (circle points) with the closed form solution (solid curves). Figure 1 shows the excellent agreement for a sphere radius $a = 1.0$, baseline $b = 0.1$ and standoffs S from 0.1 to 1.0. Figure 2 gives results when the baseline is increased to 1.0; agreement is still excellent although a small deviation is observed about the point of nearest approach.

It may be noted here that the physical optics results may be as accurate as the closed form solution. In the latter case convergence problems arise when source and receiver are the same distance from the center of the sphere; i.e., in the present case, when the system is at or near the point of closest approach.

Figures 3 and 4 illustrate the effect of reducing the sphere radius to 0.1. It may be observed that agreement with the exact results is reasonable around the nearest approach for small standoff and the error increases both for greater standoff and when the system is furthest removed from the point of nearest approach. The maximum error is at most 10 dB for a signal strength of 50 dB below peak response.

It may also be noted in connection with Figure 3 that several scanning mesh parameters were tried varying from .1 to .01 skin depth. A noticeable change was observed in going from 0.1 down to 0.03 but beyond that any further mesh refinement has negligible effect.

The curves of Figure 5 give physical optics results for the infinite cylinder of unit radius with the system traverse occurring perpendicular to its axis. Results are very similar to that for the sphere. This illustrates the limited angular region over which the magnetic dipole is effective and confirms earlier work reported in Reference 2.

Figure 6 gives results for the super-ellipsoid: ellipsoidal in longitudinal section and super-elliptic of order 4 in the transverse section. The resulting curves have the form to be expected for a scatterer which is broader and flatter than the sphere. It should also be realized that the "corner" of the super-ellipse may not be adequately represented by a scan parameter of one-tenth skin depth, resulting in some smoothing of the response curve.

CONCLUSIONS

(i) The physical optics approximation gives excellent results over a wide range of parameters when applied to scattering in a lossy medium.

(ii) The range of parameters over which this theory may be used coincides with those of interest in the study of conducting inhomogeneities in a lossy environment.

(iii) Both qualitatively and quantitatively, the results for the sphere may be extrapolated to a large degree to yield information on more complex shapes such as the spheroid with super-elliptic transverse cross section.

(iv) A method has been investigated and proven accurate for predicting the electromagnetic signature of conducting objects in the ocean environment for object sizes down to a fraction of the skin depth for the given signal frequency.

(v) The nature of the signatures obtained shows that accurate position indication may be obtained using this system.

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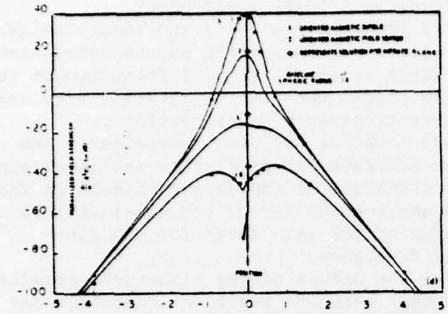

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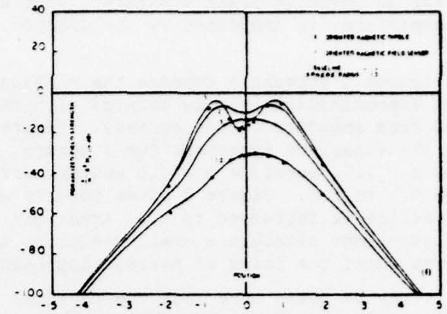

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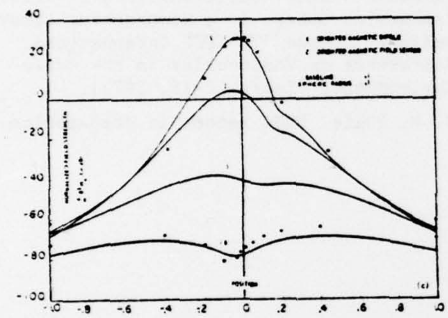

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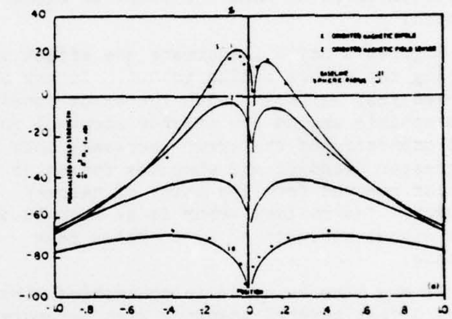

(4)

Figures 1-4 Comparison of Physical Optics Approximation with Exact Results for the Sphere.

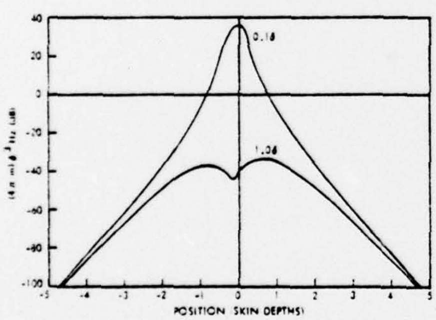

Figure 5

Physical Optics Results for Infinite Cylinder, Radius 1δ, Baseline 0.1δ. Path Normal to Cylinder Axis.

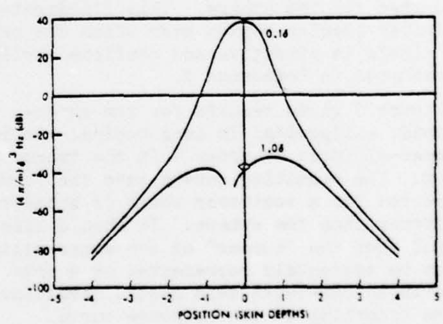

Figure 6

Physical Optics Result for Superelliptic Spheroid; Semiminor Axis 1δ, Semimajor Axis 5δ, Baseline 0.1δ. Path Normal to Major Axis.

A MODIFIED PHYSICAL OPTICS TECHNIQUE FOR OBTAINING ELECTROMAGNETIC SIGNATURES OF OBJECTS WITH EDGES TOTALLY IMMERSED IN THE OCEAN [I]

D.M. Bolle

Reprinted, with permission, from OCEANS '74, IEEE Publication No. 74 CHO 873-0 OCC, pp. 291-292. (Conference held 22-23 August 1974 at the Hotel Nova Scotian, Halifax, Nova Scotia.)

INTRODUCTION

In previous papers (1,2) the utility of the physical optics approximation in predicting the electromagnetic signatures of conducting bodies immersed in the ocean was investigated. It has been shown that the physical optics approximation gave excellent agreement with exact results for spheres or radius of one skindepth or larger of the electromagnetic radiation in sea water and good results for spheres down to a radius of one tenth of a skindepth. The greatest disagreement incurred between the exact and approximate results was about three dB in the latter case.

The results were subsequently extended to more complex bodies such as the cylinder, ellipsoid and superellipsoid.

In this work the results obtained in the next logical sequential step in generalizing this approach to objects with sharp edges will be presented.

DISCUSSION

It is desirable to be able to predict the signature, not only of smooth objects, but also of composite objects which are largely smooth but may have sharp edges and sharp, acute-angled protrusions.

To examine the utility of the physical optics approximation when the radius of curvature of parts of the surface of the objects are much smaller than the skindepth, the magnetic dipole in the vicinity of the edge of a semi-infinite conducting plane was considered.

This geometry can serve as a canonical problem and produces the most severe test for the physical optics approximation. Secondly, exact solutions are available (3,4) and thus the necessary comparison can be made. It is expected that the physical optics approximation will not suffice for all orientations of the dipole with respect to the direction of the edge of the half-plane. Thus, the availability of exact solutions will allow the evalutations of a modified physical optics approach.

Once an adequate model has been established for predicting the current distributions induced near edges, we can introduce such modelling into the master program and calculate directly the response of a large class of objects exposed to a magnetic dipole source and an orthogonally oriented magnetic field component sensor.

THEORY

The physical optics approximation consists of replacing the exact current distribution at a point on a curved conducted body by the surface current that would be induced on a infinite plane if it were tangent to the curved body at the point of interest. Thus, for an infinite plane the result is exact and, as the curvature increases, we can expect deterioration in the results obtained. The fact that we are considering a system immersed in a lossy medium, i.e., sea water, accounts for the fact that we obtain excellent to good results down to large curvatures, i.e., radii of curvature down to one tenth of a skindepth. At a sharp edge we must expect gross errors since it is well-known that surface current component parallel to an edge should exhibit singular behavior and, for a semi-finite plane, the current component parallel to the edge will increase as $r^{-1/2}$ where r is the distance from the edge. Surface current components normal to the edge must vanish as r goes to zero. However, physical optics predicts constant values for both components in the vicinity of an edge.

To construct a Modified Physical Optics approximation presents no great difficulty. It is an easy matter to write suitable approximations for the current components in terms of two parameters then four, etc., until we have achieved an accuracy adequate to our purpose.

Previous studies of surface currents near the edge of acute angled wedge-shaped semi-infinite conductors illuminated by a plane electromagnetic wave give considerable insight into the approximations to be employed (5).

Thus, the physical optics approximation

$$\underline{J} = 2\underline{n} \times \underline{H}_i \qquad (1)$$

where $\underline{J}$ is the surface current density, $\underline{n}$ the surface normal and $\underline{H}_i$ the incident magnetic field intensity, is modified to become

$$\begin{aligned} \underline{J} = {} & 2n(\underline{n} \times \underline{H}_i) \cdot (\underline{\tau} \times \underline{n})(1 - e^{-\alpha r})(\underline{n} \times \underline{\tau}) \\ & + 2(\underline{n} \times \underline{H}_i) \cdot \underline{\tau}(1 + Ar^{-1/2})\underline{\tau} \end{aligned} \qquad (2)$$

where $\underline{\tau}$ is a unit vector parallel to the edge. As the half-plane is allowed to assume a wedge shape so α and A will change as will the exponent of r in the second term for $\underline{J}$.

RESULTS

Computer programs were prepared yielding the magnetic field sensed by a detector oriented normal to the magnetic dipole at a fixed distance from the dipole source as this source traversed a path normal to the edge of the semi-infinite conducting plane. The methods employed were; first, the physical optics approximation; secondly, exact results based on work by Bowman and Senior (6); and, thirdly, the modified physical optics approximation as given by equation (2).

The two figures give samples of the computed results. The path of the dipole source -- sensor system was normal to the edge of the half-plane and parallel to that plane. The separation between the source and the sensor was fixed at one tenth of a skindepth for these calculations and the dipole oriented normal to the semi-infinite plane ($x > 0$, $y = 0$).

Figure 1 shows sample calculations obtained from the exact theory for that component of the suitable normalized magnetic field intensity which is zero in the absence of any perturbing object in the vicinity of the dipole. Above the semi-infinite plane and away from the edge the results rapidly approaches the limit value obtained from image theory for the magnetic dipole above an infinite perfectly conducting plane, while beyond the edge the results again rapidly approach the asymptotic slope of 30 dB's/skindepth. The 'edge-effect' is evidently limited to a region not extending beyond one and a half times the stand-off, i.e., the distance of the path above the surface $y = 0$, which contains the semi-infinite plane.

Figure 2 shows the results of the calculations based on the exact theory (curve A) for the case where the stand-off is half a skindepth and compares it to the results of the physical optics approximation (curve B) as well as the results obtained from the Modified Physical Optics approximation with the parameters values $A = 2.0$, $\alpha = .5$, (curve C), and $A = .1$, $\alpha = 1.0$ (curve D). It is seen that the two parameter approximations allow wide latitude in increasing the accuracy of the physical optics approximation and models the behavior of the system in the neighborhood of the edge appropriately.

It is concluded that the physical optics method may be modified to include objects with sharp edges and that this method is therefore sufficiently flexible to allow computation of the electromagnetic signature of complexly shaped perfectly conducting metallic objects in the ocean.

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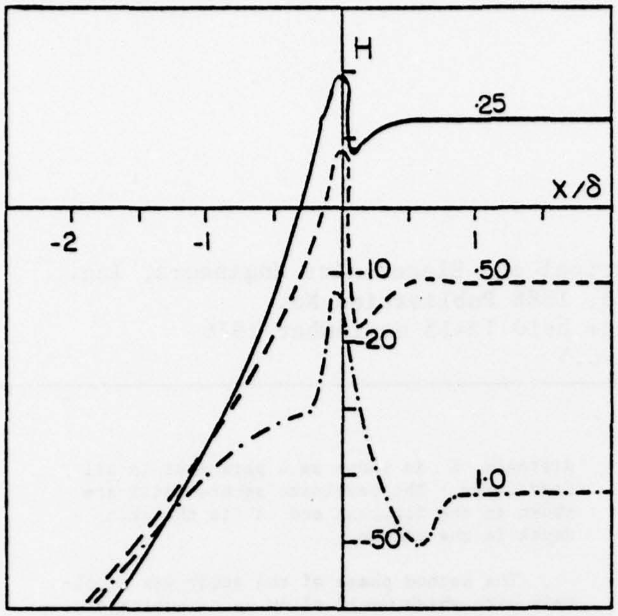

Figure 1. The exact results for $H = (4\pi\delta^3/m)H_x$ in dB versus x/δ with the stand-off in skin depth as a parameter.

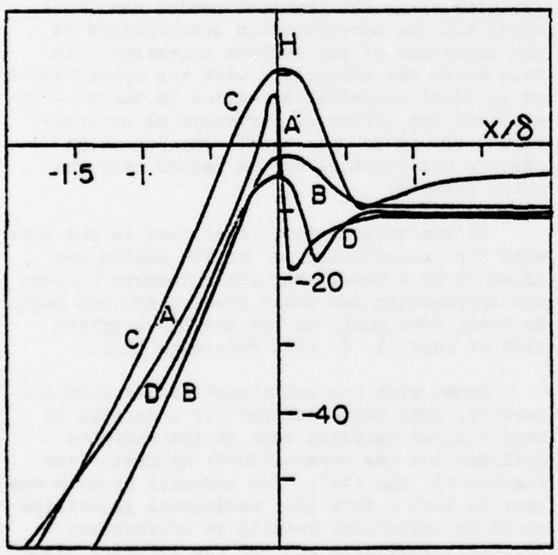

Figure 2. The approximate results compared with the exact results for a stand-off of .5δ. A - the exact result, B - the physical optics approximate, C - the modified physical optics approximation (A = 2.0, α = 0.5), D - m.p.o. (A = 0.1, α = 1.0).

A MODIFIED PHYSICAL OPTICS TECHNIQUE FOR OBTAINING ELECTROMAGNETIC SIGNATURES OF OBJECTS WITH EDGES TOTALLY IMMERSED IN THE OCEAN [II]

D.M. Bolle
R.A. Bowden

Abstract

The objective of this study was to develop an approximate method for predicting, with acceptable accuracy, the electromagnetic field scattered by perfectly conducting bodies of complex shape immersed in a lossy medium, i.e. the ocean, when subjected to the field of an oscillating magnetic dipole source.

Introduction

Since the class of scatterers of interest had characteristic dimensions of the order of, or larger than, the electromagnetic wavelength or the 'skin depth' in the lossy medium and, furthermore, were initially restricted to those having smooth bounding surfaces, it was decided to investigate the physical optics approximation. The approach appeared particularly attractive because of the ready adaption of the computer program to handle a wide variety of scattering shapes.

The study consisted of four interlocking parts. First, it was necessary to determine the effectiveness and accuracy of the physical optics approximation in this environment. To this end not only was a computer program developed which allowed the calculation of the scattered field from a smooth, but as yet unspecied, body shape but also, using a formulation by D. S. Jones [1], the exact solution for the magnetic dipole field scattered by a perfectly conducting sphere immersed in a conducting medium was programmed and obtained.

Some sample results obtained with this program are shown in figure (1). These results are taken from earlier work [2] which we reported on at Ocean '72. The results shown are for the case where we have a magnetic dipole source and a magnetic field sensor pair passing the spherical inclusion with the magnetic dipole oriented in the direction of motion and the magnetic sensor directed normal to the path and in the plane containing the coordinate center of the sphere. The separation between the dipole and sensor is $.01\delta$ for (1a) and (1b) and $.1\delta$ for (1c) and (1d) while the minimum approach distance S is shown as a parameter in all four cases. The pertinent sphere radii are shown in the figures, and δ is the skin depth in the medium.

The second phase of the study was to obtain data which would allow us to evaluate the range of the parameters for which the physical optics approximation gave results which were adequate, say within three db, when compared with the exact results obtained for the spherical inclusions. The physical optics approximation assumes that on curved perfectly conducting bodies the total local tangential magnetic field intensity is twice that of the incident field. Thus, for an infinite plane the physical optics result is exact but the approximation deteriorates as the curvature of the surface increases. In this sense the comparison with the sphere gives us an ideal canonical situation in which we can evaluate the effect of curvature on accuracy. Figure (2) gives some sample results which compare the physical optics method with the exact results.

It was surprising to find that in the case when the conductivity σ of the medium was taken to be 4 mhos/meter the agreement between the approximate and exact results did not begin to break down until we had reached a sphere size of only $.1\ \delta$ (see reference [3]).

Armed with the confidence gained from the results, data were obtained for a variety of more complex surfaces such as the infinite cylinder and the superelliptic spheroid (see figures (3) and (4)). The computer program was cast in such a form that additional geometries could be introduced readily as subroutines. Currently available are (1) the infinite plane, (2) the infinite cylinder, (3) the sphere, (4) the prolate or oblate spheroid, (5) the superelliptic spheroid, (6) the hyperbolic cylinder.

The reason for including the infinite plane was to allow the numerical procedures to be checked under the condition where the physical optics approach does, in fact, yield the exact and correct result thereby isolating procedural and numerical sources of error from those

introduced due to surface curvature where the P. O. approach is not exact.

The third part of the research program consisted of extending the physical optics approach to bodies with edges.

A direct extension, once a suitable canonical geometry for testing purposes was chosen, was rather straightforward in that only a further subroutine needed to be introduced into the master program. The choice of the canonical geometry was limited to those few for which exact solutions already existed. For this reason the semi-infinite perfectly-conducting plane was chosen. Two approaches leading to exact solutions are described in the literature [4].

Some initial results were generated which made use of the direct physical optics method. Sample results are shown in figures (5) and (6). It is clear, however, that the physical optics approximation does not generate the appropriate singularity behavior in the field structure near the edge. For example, in the case of the semi-infinite plane the component of the field normal to the edge, i.e., the surface current density component parallel to the edge, must behave as $r^{-1/2}$ as the edge is approached [5] whereas the total surface current density normal to the edge must vanish. The program was therefore modified to allow the introduction of two parameters which could subsequently be adjusted to minimize the discrepancies between the exact and approximate results and allow the extension of the P. O. approach to bodies with corners and edges, i.e., the induced surface current $\underline{J}_s$ was given the form

$$\underline{J}_s = 2(\underline{n} \times \underline{H}_i) \cdot \{(\underline{\tau} \times \underline{n})(1 - e^{-\alpha r})(\underline{n} \times \underline{\tau}) + \underline{\tau}(1 + Ar^{-1/2})\underline{\tau}\}$$

where $\underline{n}$ and $\underline{\tau}$ are unit vectors normal and tangential to the edge of the half-plane, $\underline{H}_i$ in the incident magnetic field intensity, α and A are the two adjustable parameters. Figure (7) shows the effect of changes in these parameters.

The fourth and final part of the current program consists of obtaining numerical results from the exact solutions for the canonical geometry. This effort is complicated by the fact that, as in the case for the exact solution for the spherical geometry, special functions must be generated (Hankel functions) which have complex arguments. At this writing these results have just become available. In figure (8), however, we display the exact solution for the semi-infinite plane but for the edge scattered term which has not, as yet, been included.

Conclusion

This paper discusses the current status of an investigation into the use of the physical optics approximation in magnetic dipole scattering from perfectly conducting inclusions in an imperfectly conducting medium. The inclusions are generally taken to be smooth but may in addition exhibit edges and corners.

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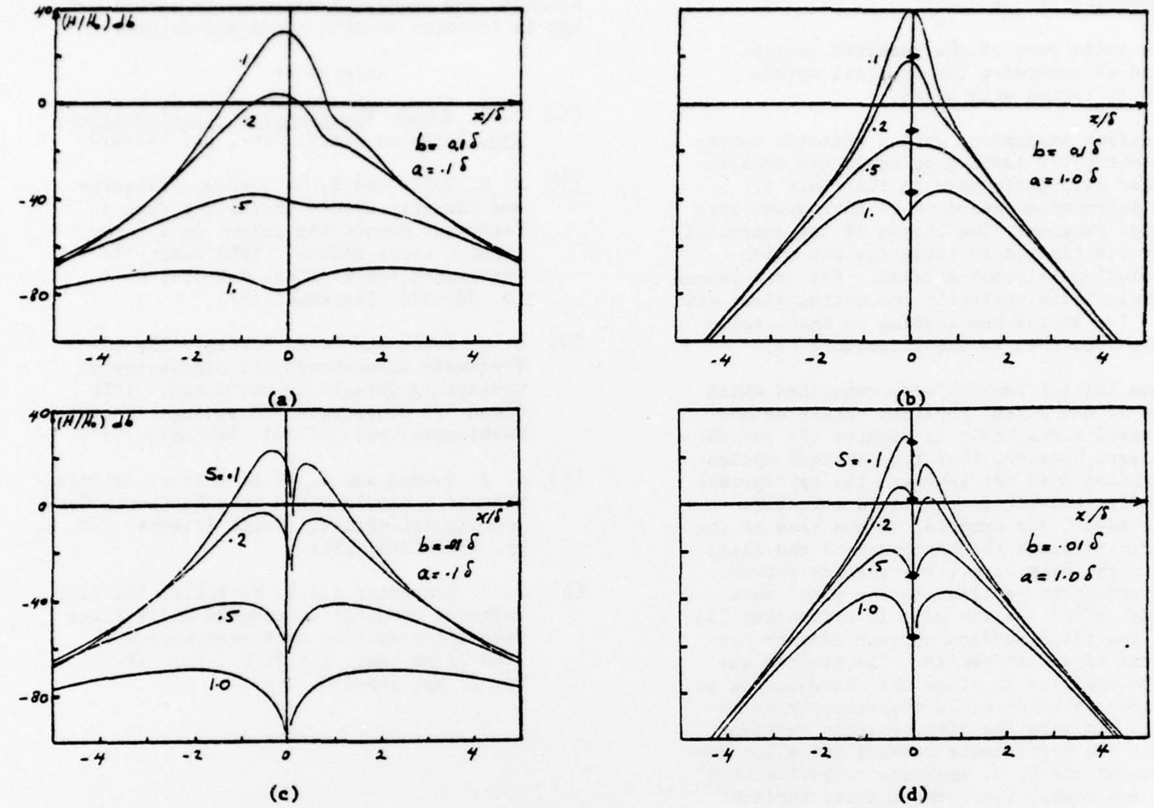

Figure 1: The Perfectly conducting Sphere in the Ocean (= 4). The Exact Solution.
a = sphere radius , b = distance dipole-detector.

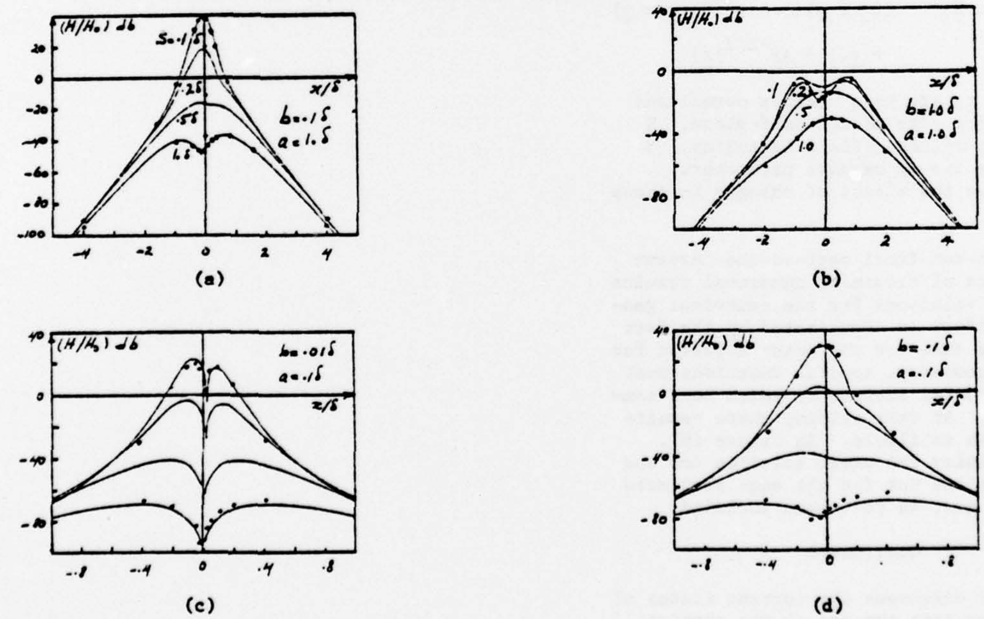

Figure 2: The Physical Optics Approximation and the Exact Solution Compared.
Spere radius = a. S = nearest approach distance.

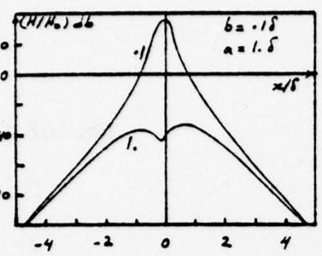

Figure 3: The Infinite Cylinder.
Path normal to cylinder axis.

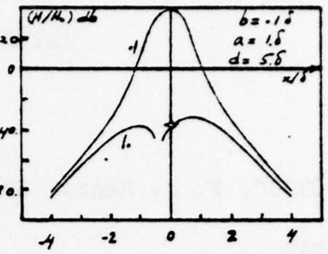

Figure 4: The Superelliptic Spheroid.
Path normal to major axis.

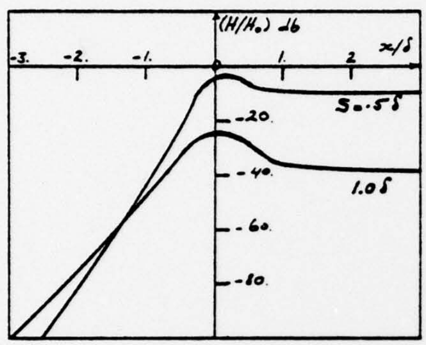

Figure 5: The Physical Optics Result
for the Semi-infinite Plane.
Path normal to edge and parallel to plane

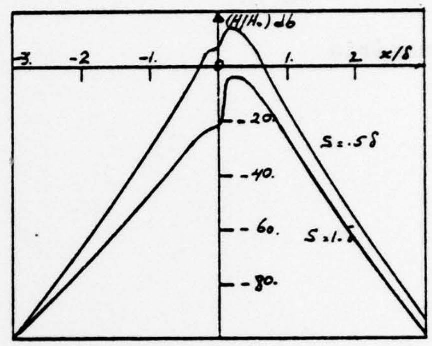

Figure 6: The Physical Optics Result
for the Semi-infinite Plane.
Path normal to edge and to plane.

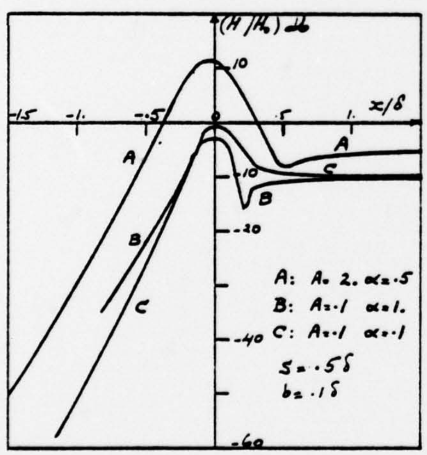

Figure 7: The Modified Physical Optics
Result for the Semi-infinite Plane.

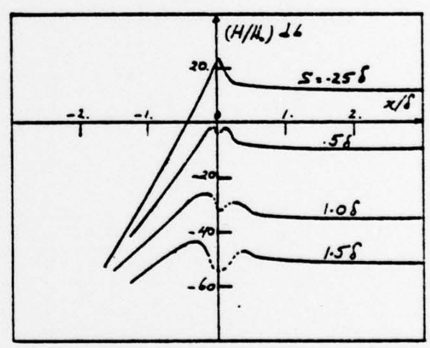

Figure 8: The Exact Result for the Semi-
Infinite plane (Edge scattered term not
included).

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